



One-of-a-kind facility produces power from ocean water

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Keahole Point, near Kailua-Kona on Hawaii's "Big Island," is the location of the Natural Energy Laboratory of Hawaii (NELH). The 870-acre site supports a variety of research, demonstration, and commercial projects. An abundance of sunshine, a mild climate, and ready access to deep ocean waters make this an ideal location for aquaculture, solar, and ocean experiments. NELH is also the home of the world's only operating experimental OTEC plant.

The OTEC process

OTEC (ocean thermal energy conversion) uses the difference in temperature between surface and deep sea water to generate electricity. This is done in a closed or open cycle process.

Closed cycle OTEC was first envisioned by French engineer Jacques-Arsène D'Arsonval in 1881. Sea water, warmed by solar radiation, vaporizes a low boiling point fluid, such as ammonia, in a heat exchanger. The expanding vapor drives a turbogenerator before being liquefied in a condenser by cold sea water pumped from the ocean depths.

In 1920 one of D'Arsonval's students, Georges Claude, proposed an open cycle OTEC system (OC-OTEC). When warm sea water is injected into a near vacuum, it vaporizes. The resulting steam expands through a low-pressure turbogenerator before being condensed with cold sea water. The cycle is "open" because no further use is made of the water, and it returns to the ocean.



OC-OTEC Experimental Facility at Keahole Point.



Vacuum compressors with temperature detectors mounted on top. Photos courtesy of The Pacific International Center for High Technology Research

Although the principles were well understood, Claude's work and efforts sponsored by the French government during the 1940's failed to produce a net power output — it took more energy to pump sea water from the ocean than the plants produced. Not until the Arab oil embargo of the early 1970's did interest turn to "renewable" energy resources. Recently, the economic viability of OTEC has been improved by advances in evaporator, heat exchanger, and condenser technology, and favorable results from experiments with sea water pipes.

Plant description

The OC-OTEC Experimental Facility at Keahole Point is an open cycle plant funded by the U.S. Department of Energy and the State of Hawaii. The facility was designed by the Solar Energy Research Institute (now the National Renewable Energy Laboratory), Golden, Colorado, and The Pacific International Center for High Technology Research (PICHTR), Honolulu, Hawaii. The turbine generator was designed by Mechanical Technology Incorporated, Rochester, New York, and the high speed vacuum compressors were designed by Barber-Nichols, Arvada, Colorado. The plant began operation in December 1992, and is funded for operation until early 1995. The OC-OTEC Experimental Facility was built and is operated by PICHTR.

Since the plant is located on a lava flow about 152 m (500 ft) from the coast, ocean water must be pumped to it. High-density polyethylene pipes siphon warm surface water from near the shore and cold sea water from 671 m (2,200 ft) deep into a pump station operated by NELH. The pump station supplies ►

water to the OC-OTEC facility and other users at the laboratory.

Figure 1 is a cross-sectional illustration of the plant. The turbine is supported by a concrete vacuum vessel 7.6 m (25 ft) in diameter and 9.5 m (31 ft) high. A synchronous electrical generator made by Kato is located above the turbine assembly and outside the vacuum enclosure. Six high-efficiency vacuum compressors are mounted on top of the structure, and additional vacuum and water pumps are mounted at the base of the structure.

Warm water from the NELH supply line enters an annular flash evaporator at 620 kg/s (9600 gpm). The evaporator consists of a 0.6 m (2 ft) diameter circular manifold with 13 vertical spouts at the periphery of the vessel. The vacuum compressors pull down the pressure in the vessel. Approximately 0.5%, or 3.5 kg/s (54 gpm) of the warm water flow flashes to steam at 2600 Pascal (0.38 psia). The remaining warm liquid falls into the evaporator discharge pool and exits through the warm water discharge line. Occasionally, crustaceans and other debris must be cleaned from the bottom of the discharge pool.

The steam flows up from the evaporator and enters the turbine radially inward. The steam exits the turbine axially in the center of the vessel and travels downward around the diffuser assembly to an open condenser. A conical exhaust diffuser is used to raise the exhaust pressure to the condenser nominal pressure of 1300 Pascal (0.19 psia). Interestingly,

the pressure differential across the turbine is approximately 1/6 psi, and plywood is used for the diaphragm between the turbine inlet and exhaust.

Meanwhile, cold sea water has been entering the cold water riser in the bottom center of the vacuum structure. The cold water in the riser is lifted and spills over radially into a two-stage direct-contact structured-packing condenser. The steam mixes with and condenses in the cold water, and the resulting liquid exits the condenser discharge pool via the cold water discharge line. Noncondensable gases and a small amount of uncondensed steam are compressed and exhausted in the multiple-stage vacuum-compression system.

Approximately 150 kW is required to operate the pumps at the plant. For a surface water temperature of 26°C (79°F) and a deep water temperature of 6°C (43°F), the turbine generator nominal gross output is 210 kW. However, the surface water temperature varies, and the highest surface temperature to date was 27.5°C (81°F). This resulted in 255 kW gross power produced, and a net power production of 103 kW — a world record for OTEC. The OC-OTEC Experimental Facility has successfully demonstrated net power production, and the feasibility of the turbine and vacuum-compression subsystems.

Low pressure open-cycle turbine

The turbine is a vertical-axis, mixed-

flow type. Because it is similar in characteristics to a hydroturbine, it was manufactured by American Hydro. It is 3.1 m (10 ft) in diameter, weighs 8160 kg (18,000 lb.) (turbine and generator), and has a blade tip speed of approximately 274 m/s (900 ft/s) at 1800 rpm. A fluid clutch between the turbine and generator mitigates electrical load swings caused by the slow response of the heavy rotor system to minor frequency changes in the local power grid.

A Bently Nevada 3300 Monitoring System is used to monitor the turbine. Two proximity probes, mounted 90 degrees apart on each of the two radial sleeve bearings, supply signals to 3300/16 Dual Vibration Monitors. The probes are mounted in Bently Nevada probe housing assemblies that allow external adjustment or replacement of the probes. The thrust bearing is a rolling element type, so an accelerometer and 3300/25 Dual Accelerometer Monitor are used to monitor this machine point.

PICHTER is pleased with the operation of both the 3300 Monitoring System and the turbine. Based on an observed correlation between lubricating oil viscosity and vibration, information from the Bently Nevada 3300 System has been used to optimize lube oil temperatures.

High efficiency vacuum compressors

Five stages of vacuum compression generate the 1% to 2% atmospheric vac-

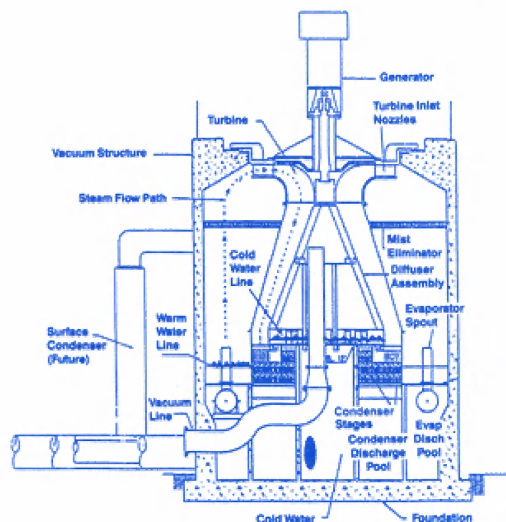


Figure 1
Cross section of the plant.

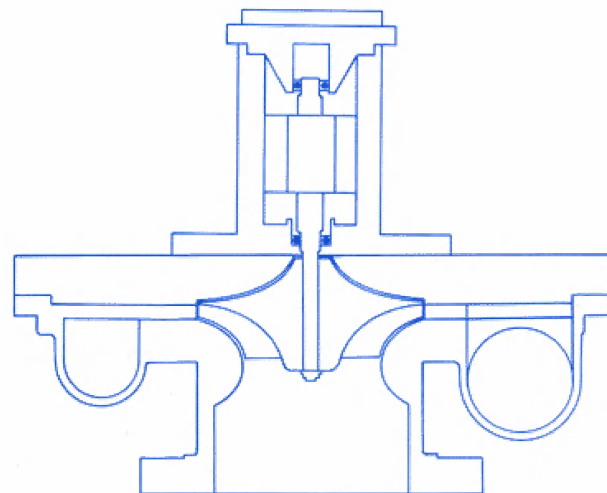


Figure 2
Cross section of the vacuum compressor.

uum required for the OC-OTEC plant. The first four stages consist of Barber-Nichols centrifugal vacuum compressors with integral electric motors (both the motor and compressor operate in the vacuum). Figure 2 is a cross-sectional illustration of a vacuum compressor.

The OC-OTEC process required a completely new vacuum compressor machine design, with performance being the primary design criterion. This meant high design speeds — up to 42,850 rpm for the fourth stage. Hybrid ball bearings were selected because these speeds exceed the recommended maximum for conventional steel, grease-packed bearings.

During operation of the vacuum compressors, PICHTR experienced frequent failure of the bearings, and at one point suspected that the rotors had gone out of balance. As part of PICHTR's and Barber-Nichols' investigation of the problem, a balance stand with a Bently Nevada Digital Vector Filter (DVF-3), patterned after Barber-Nichols' balance equipment, was constructed on site. After several balancing iterations, unbalance was discounted as the root cause of the bearing failures.

Bently Nevada's Machinery Diagnostic Services (MDS) was called in to help troubleshoot the problem. An MDS engineer traveled to the job site and instrumented two of the compressors. The

transducers consisted of accelerometers to measure casing absolute radial vibration, proximity probes to measure rotor axial position, and an infrared sensor to measure the shaft end temperature (approximately 5 cm (2 inches) from the upper bearing).

MDS recorded the failure of an upper radial bearing on a higher speed unit using Bently Nevada's ADRE® for Windows System. No increase in vibration at bearing frequencies was noted, indicating that dynamic failure of bearing elements was not the cause of the problem. Figure 3 is an ADRE for Windows waterfall plot of the spectral data prior to the failure.

However, high shaft end temperatures (over 300°F) were noted before failure of the bearing. Figure 4 is an ADRE for Windows plot of the temperature excursion. The bearing failure was characterized by breakdown of the grease and subsequent meltdown of the phenolic cage material. The MDS engineer suggested that thermal growth may have been the root cause of the high temperatures.

After analyzing the MDS data and consulting with bearing experts, Barber-Nichols engineers developed a probable theory for the bearing behavior. Greater thermal growth of the inner race relative to the outer race could have reduced the bearing clearances, causing an increase

in bearing temperature, further reduction in clearance, and eventual bearing failure.

Based on Barber-Nichols' recommendation, the original hybrid bearings were reballed with a smaller diameter ball, thereby increasing the internal clearance. Also, grease reservoirs were established around the bearing, and a different grease was selected for the application. Initial results are promising, but time will tell if acceptable bearing life will be achieved. PICHTR has added temperature sensors to the compressors, and will periodically monitor the bearings with an accelerometer.

The future

Further operation and testing at Keahole Point will be conducted to learn more about the OC-OTEC process. A plant of this size has an efficiency of from 20%-40%. Commercial plants would be approximately 100 MW with an efficiency of up to 70%.

PICHTR is currently working on the preliminary design of a 5 MW floating demonstration plant that would combine elements of open- and closed-cycle OTEC. Placing the plant in the ocean reduces the limitations caused by the large quantities of water required by the process. PICHTR's vision is to see the electrical needs of the entire state of Hawaii met using 17 offshore OTEC power plants. ■

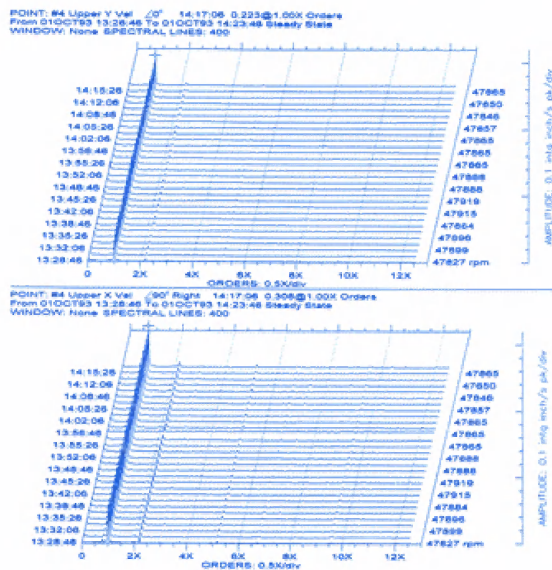


Figure 3
ADRE® for Windows waterfall plot of spectral data prior to the failure.

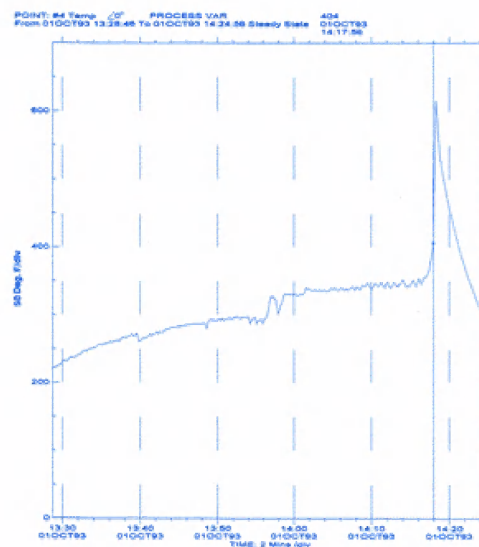


Figure 4
ADRE® for Windows plot of the temperature excursion.